Two neutrino double beta decay for the $0^+ \rightarrow 2^+$ transition

Yash Kaur Singh[1], R. Chandra[1],* Brijesh Shukla[2], P. K. Rath[2] and P. K. Raina[3]
[1] Department of Applied Physics, Babasaheb Bhimrao Ambedkar University, Lucknow - 226025, INDIA
[2]Department of Physics, University of Lucknow, Lucknow, 226007, INDIA
[3]Department of Physics, IIT Ropar, Nangal Road, Rupnagar, Punjab – 140001, INDIA
* email: ramesh.luphy@gmail.com

Introduction

The nuclear double beta (ββ) decay has attracted a lot of attention in theoretical as well as experimental studies [1,2,3] due to its capability to test nuclear structure effects and physics beyond standard model (SM) of electroweak unification. The two neutrino double beta $(\beta\beta)_{2\nu}$ decay is a process of second order in weak interaction and is allowed in SM. The neutrinoless double beta $(\beta\beta)_{0\nu}$ decay is far more interesting as it violates the lepton number conservation by two units and hence its observation can lead the physics beyond SM. Further, the detection of $(\beta\beta)_{0\nu}$ decay will immediately imply the Majorana nature of neutrinos. In $(\beta\beta)_{2\nu}$ decay, the total angular momentum of four S-wave leptons can be 0,1 or 2 and is equal to the total angular momentum transferred between the parent and the daughter nuclei. The lowest 1^+ state in the final nucleus of any ββ decay candidate lies much higher than the first excited 2^+ state. Hence, the $0^+\rightarrow1^+$ transition is much less probable than the $0^+\rightarrow0^+$ and $0^+\rightarrow2^+$.

The inverse half- life of $(\beta^-\beta^-)_{2\nu}$ decay is product of exactly calculable phase space factor and nuclear transition matrix elements (NTMEs) $M_{2\nu}$. The NTMEs can be extracted using the experimental half-lives. It is observed that in all cases of $(\beta^-\beta^-)_{2\nu}$ decay, the NTMEs are sufficiently quenched. The main motive of all theoretical calculations is to understand the physical mechanism responsible for the observed suppression of $M_{2\nu}$. Hence, the validity of different nuclear models can be tested by calculating $M_{2\nu}$ for $0^+\rightarrow0^+$ transition and comparing them with the experimental value. As the $0^+\rightarrow2^+$ transition of $(\beta\beta)_{2\nu}$ decay is not observed experimentally so far, the present theoretical predictions can be checked against the $0^+\rightarrow0^+$ transition only. It is noticed that there is large spread in the $M_{2\nu}$ extracted from experimental half-life $T_{1/2}^{2\nu}$ of $(\beta^-\beta^-)_{2\nu}$ decay for the $0^+\rightarrow0^+$ transition and due to this large spread the NTMEs $M_{2\nu}$ calculated in various nuclear models, in spite of having noticeable variations, agree with the experimental results. Once the $0^+\rightarrow2^+$ transition of $(\beta\beta)_{2\nu}$ is observed, it can be a crucial add on to check the validity of various nuclear models employed to study ββ decay. Further, a reliable theoretical prediction will supplement the experimental designing and planning to study this particular mode of $(\beta\beta)_{2\nu}$ decay. Moreover, the observation of $(\beta\beta)_{0\nu}$ decay for $0^+\rightarrow2^+$ transition may help in discriminating finer issue like dominance of Majorana neutrino mass or the right handed current.

The PHFB model using summation method [4] has been successfully applied to study the $(\beta^-\beta^-)_{2\nu}$ decay for $0^+\rightarrow0^+$ transition [5,6]. In the present work we have studied the $(\beta^-\beta^-)_{2\nu}$ decay for $0^+\rightarrow2^+$ transition using summation method.

Theoretical framework

The inverse half-life of the $(\beta^-\beta^-)_{2\nu}$ decay for $0^+\rightarrow2^+$ transition is given by

$$\left[T_{1/2}^{2\nu}\left(0^+\rightarrow2^+\right)\right]^{-1} = G_{2\nu}(2^+)\left|M_{2\nu}(2^+)\right|^2 \qquad (1)$$

where the integrated kinematical factor $G_{2\nu}(2^+)$ can be calculated with good accuracy and NTME $M_{2\nu}(2^+)$ is given by

$$M_{2\nu}\left(2^+\right)=\sqrt{\frac{1}{3}}\sum_N\frac{\left\langle 2^+\left\|\sigma\tau^+\right\|1_N^1\right\rangle\left\langle 1_N^1\left\|\sigma\tau^+\right\|0^+\right\rangle}{\left[E_0+E_N-E_I\right]^3} \qquad (2)$$

where

$$E_0=\frac{1}{2}\left(E_I-E_F\right)=\frac{1}{2}Q_{\beta\beta}+m_e \qquad (3)$$

The summation over intermediate states can be completed using the summation method [4].

Using summation method, the NTME $M_{2\nu}(2^+)$ is given by

$$M_{2\nu}(2^+) = \sum_{\pi,\nu} \frac{\langle 2_F^+ \| [\sigma \otimes \sigma]^{(2)} \tau^+ \tau^+ \| 0_I^+ \rangle}{[E_0 + \varepsilon(n_\pi l_\pi j_\pi) - \varepsilon(n_\nu l_\nu j_\nu)]^3} \quad (4)$$

Results and discussions

The model space, single particle energies (SPE's), parameters of the pairing plus multipole (PQQHH) type of effective two-body interaction have been already given in Ref. [7]. We use four parametrizations namely, PQQ1, PQQHH1, PQQ2, and PQQHH2. The details about these parametrizations and method to fix them have been provided in our earlier work [8]. We present the results of PQQ1 parametrization in Table 1.

Table 1: Theoretically calculated NTME $M_{2\nu}(2^+)$ and half-life $T_{1/2}^{2\nu}(2^+)$ for the $0^+ \rightarrow 2^+$ transition in PQQ1 parametrization.

Nuclei	**Model**	$\mathbf{M_{2\nu}(2^+)}$	$\mathbf{T_{1/2}^{2\nu}(2^+)}$
^{94}Zr	PHFB	1.445×10^{-4}	7.038×10^{36}
^{96}Zr	PHFB	9.715×10^{-5}	7.093×10^{25}
	QRPA[9]	1.113×10^{-4}	5.403×10^{25}
^{100}Mo	PHFB	1.953×10^{-5}	1.796×10^{27}
	QRPA[9]	1.814×10^{-4}	2.081×10^{25}
^{104}Ru	PHFB	3.301×10^{-5}	9.532×10^{32}
	QRPA[9]	3.736×10^{-3}	7.444×10^{28}
^{110}Pd	PHFB	1.212×10^{-4}	5.547×10^{27}
	QRPA[9]	6.671×10^{-3}	1.830×10^{24}
^{128}Te	PHFB	1.190×10^{-6}	4.939×10^{35}
	QRPA[9]	3.055×10^{-4}	7.498×10^{30}
^{130}Te	PHFB	7.721×10^{-7}	3.602×10^{30}
	QRPA[9]	8.272×10^{-5}	3.155×10^{26}
^{150}Nd	PHFB	6.322×10^{-6}	7.693×10^{26}
	SU(3)[10]	5.380×10^{-5}	1.062×10^{25}

The phase space factors $G_{2\nu}(2^+)$ have been taken from Pahomi et al. [11] where ever available and rescaled for axial vector coupling constant g_A=1.2701 [12]. For rest of the nuclei they have been calculated by following the prescription of Suhonen and Civitarese [13] using g_A=1.2701. The calculated $M_{2\nu}(2^+)$ in present work is less than other theoretical calculations by order of 10-10^2. Rest of the results for other parametrizations will be presented and discussed in the symposium.

Conclusions

The observation of Table 1 shows that predicted $T_{1/2}^{2\nu}(2^+)$ of ^{96}Zr, ^{100}Mo, ^{110}Pd and ^{150}Nd nuclei may be reached in near future experiments. However, the predicted half-lives of rest of the nuclei under consideration are too high to achieve.

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